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Exposure to aerosol and gaseous pollutants in a room ventilated with mixing air distribution

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SUMMARY
The present study investigates the aerosol and gas dispersal in a mechanically ventilated room and the personal exposure to these contaminants. The study was performed in a full-scale climate chamber. The room was air conditioned via mixing total volume ventilation system. The room occupancy was simulated by a sitting dressed thermal manikin with realistic body shape. During the experiments monodisperse aerosols of three sizes and nitrous oxide tracer gas were generated simultaneously from one location in the room. The aerosol and gas concentrations in the bulk room air and in the breathing zone of the thermal manikin were measured. The results showed higher exposure to the contaminants measured at the breathing zone than at the ambient air. The behaviour of the tracer gas and the aerosols was similar.

PRACTICAL IMPLICATIONS
This research extends our knowledge of the effect of airflow distribution and local free convective currents around the human body on indoor exposure to different types of airborne contaminants, including aerosols and tracer gas. The results from the study can be used as input data for validating numerical and computational fluid dynamic models estimating personal exposure to indoor air pollutants.

KEYWORDS
Personal exposure, Indoor air quality, Aerosols, Tracer gas, Air distribution

1 INTRODUCTION
People spend most of their time indoors where they can be exposed to a wide variety of gaseous contaminants and particles. Most non-residential occupied rooms are mechanically ventilated in order to reduce the exposure to indoor air pollutants. Mixing air distribution is often used to provide uniform contaminant concentrations across a room by mixing the clean air supplied to the room with the polluted air present in the room. In reality however, the supply air is rarely fully mixed with the room air. This can lead to high contaminant concentration in the occupied zone. Moreover, the airflow pattern in the room may even enhance the transport of pollutants to the occupied zone (Bolashikov et al., 2012; Pantelic and Tham, 2013). Thus, assuming perfect mixing conditions in indoor environments may result in inadequate personal exposure predictions (Laverge et al., 2013; Licina et al., 2015).

The contaminant distribution at the breathing zone of occupants will depend on many factors. Some of the main factors are the used total volume air distribution method and the interaction between the free convective flow around the human body and the surrounding room air

(Licina et al., 2015; Melikov, 2015; Rim and Novoselac, 2009; Nielson et al., 2008). The type of the indoor air contaminants, whether they are gases or airborne particles (i.e. aerosols), will also contribute differently to the overall exposure.

The aim of the present study was to determine the exposure of thermal manikin to indoor gas and particle contaminants generated from the same location in a room with mixing air distribution. The paper, also, compares the behaviour of tracer gas and aerosols with different sizes.

2 METHODS

The study was performed in a full-scale climate chamber with the dimensions – 2.6 m (height) x 4.7 m (length) x 1.66 m (width). The chamber was air conditioned via mixing total volume air distribution supplying air through a two-way square diffuser (the directions in which the diffuser was blowing the air are designated in Figure 1). The air supply diffuser was mounted in the centre of the chamber's ceiling. The air was exhausted through celling mounted circular diffuser (Ø 200 mm). A dressed thermal manikin with realistic female body shape was used to simulate seated occupant in front of a table. The layout of the chamber is shown in Figure 1. The distance between the edge of the table and the manikin's abdomen was 0.1 m. The height of the manikin in sitting position was 1.3 m. The manikin consisted of 23 body segments and each segment was individually controlled to maintain surface temperature equal to the skin temperature of an average person in a state of thermal comfort. The manikin was dressed with a tight long-sleeve shirt, trousers, underwear, socks and shoes (the total clothing insulation was 0.48 clo). The total heat released from the manikin was 69 W.

During the experiments, aerosols of different well-defined sizes and nitrous oxide (N_2O) tracer gas were generated simultaneously at constant rate from one location in the room. The pollution source was located behind the manikin at1 m height and 0. 80 m distance (Figure 1). The flows of the tracer gas and aerosols were mixed in a T-piece connected to a perforated plastic ball which provided low initial velocity of the tracer gas and particles released into the room. An AGK 2000 (Palas) aerosol generator was used to generate ultrafine particles consisting of ammonium sulphate with aerodynamic diameters (dp) of 0.07 μm. A MAG 3000 (Palas) aerosol generator was used to produce fine particles with dp=0.7 μm and coarse particles with dp=3.5 μm. The fine and coarse particles consisted of crystalline NaCl core covered with condensed DEHS (bis-2(ethylhexyl)sebacate). To suppress Brownian coagulation, experiments with ultrafine, fine and coarse particles were conducted separately as every time tracer gas was released as well. The nitrous tracer gas was released from a compressed gas cylinder equipped with gas Rotameter to control the N_2O flow rate.

The tracer gas and particle concentrations were measured at the mouth of the manikin, at the total exhaust air and at the centre of the room at 1.7 m height in order to measure the concentration in the ambient air of the room. The particle number size distributions were measured with three types of aerosol spectrometers: a Scanning Mobility Particle Sizer – SMPS 3936L (consisting of an Electrostatic Classifier EC 3080, Differential Mobility Analyzer DMA 3081 and Condensation Particle Counter CPC 3775), Optical Particle Sizer OPS 3330 and Aerodynamic Particle Sizer APS 3321and CPC 3022 (all TSI Inc., USA). The SMPS measured the ultrafine particle size distribution whereas the APS and three OPSs measured the size range of fine and coarse particles. The SMPS and APS were used as a control measure only to monitor the number size distribution of the fine and coarse particles during the measurements. The SMPS was also used to monitor the total number concentration of ultrafine particles in the breathing zone of the manikin, while CPC was measuring the total

number concentration in other two locations. In order to measure the ultrafine particles concentration at the three locations, an electrically actuated 2-way valve was used to switch automatically the sampling between the exhaust and the centre of the room (ambient air). The switching of the valves was every 5 min. The sampling at the mouth was without switching (i.e. the sampling at this position was continuous). The time resolution of the SMPS was 5 min (3 min upward scan, 1 min downward scan, 1 min waiting). In the case of fine particles APS was sampling together with one of the OPS in the breathing zone of the manikin, while the other two OPSs were placed at the same spots like the sampling tubing for ultrafine particles (exhaust and centre of the room).The OPSs sampling time was 10 seconds. The tracer gas concentration was measured simultaneously in all locations using an Innova 1303 multi-channel sampler and a photoacoustic Innova 1312 multi-gas monitor. The sampling time of the Innova gas monitor was 40 sec/channel.

The experiments were carried out at 6 air changes per hour (ACH). The air temperature inside the chamber was controlled and kept at 23.5±0.2ºC during all experiments. The temperature around the chamber was kept at 23.5±0.2ºC as well. The relative humidity was measured to be in the range of 35±5%. The thermal manikin was the only heat source in the chamber.

The average pollution concentration for both particles and tracer gas was determined during the time period of steady state conditions. The results were normalized by the concentration at the exhaust air. When the normalized concentration is less than “1” it means that the concentration obtained at the measured location (mouth or ambient air) was lower than the concentration at the exhaust (i.e. lower contaminant exposure). The uncertainties of the measurements are given in the following results as error bars on the column chart. The uncertainties were calculated as the ratio of standard deviation to mean concentration obtained for each location. The standard deviations and the mean were calculated based on 30 repeated measurements for the tracer gas, 74 for the coarse and fine particles, and 2400 for the ultrafine particles (sampled with the CPC using the 2-way valve). The repeated measurements for the ultrafine particles sampled at the mouth were 20.

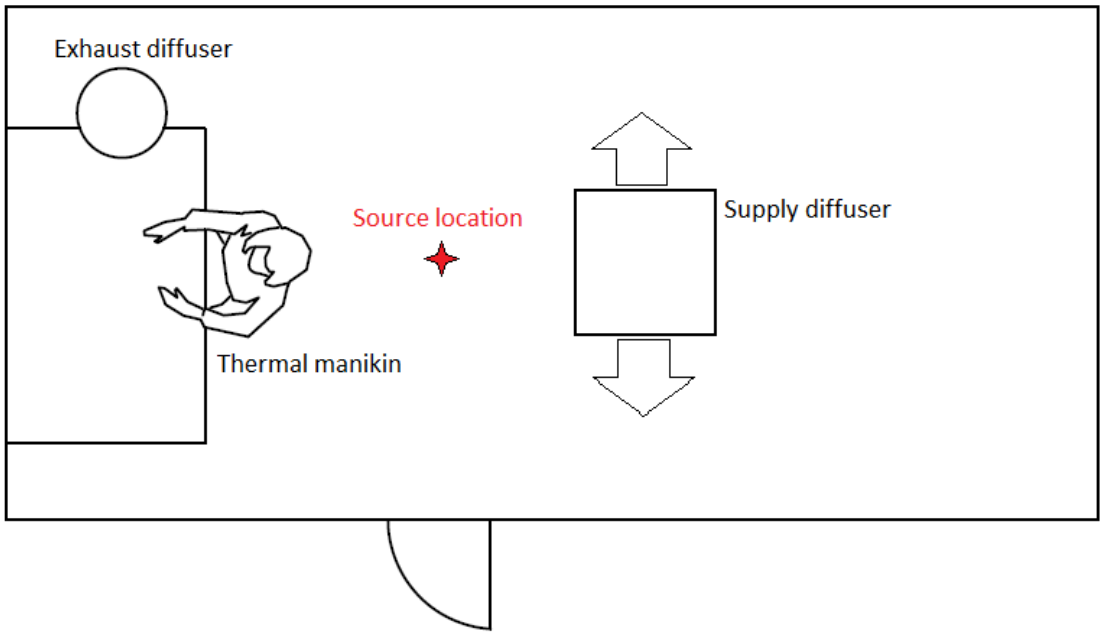

Figure 1. Top view sketch of the chamber layout.

3 RESULTS

Figure 2 shows the gas and aerosol normalized concentration measured at the mouth of the manikin and in the ambient air of the room. In the figure, the normalized concentration at the mouth tends to be higher than the concentration in the ambient air for both gas and aerosol pollutants (except for the fine particles). This indicates that the exposure of the manikin to the gas and particles was higher than the background pollution concentration.

As we can see from the results in Figure 2, there are no large differences between the tracer gas normalized values and the normalized particle concentration. The concentration distributions of the aerosols at both measured locations appear to be similar to that of the tracer gas. The highest percentage difference between the normalized gas and particles concentrations was 18%.

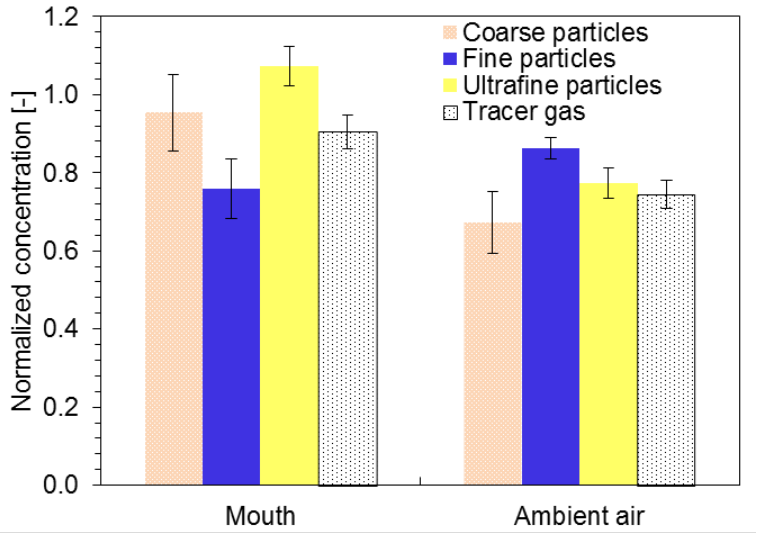

Figure 2. Normalized concentration of tracer gas and aerosols.

4 DISCUSSION

Rim and Novoselac (2009) found that in the room ventilated with mixing air distribution (4.5 ACH), uniform concentration patterns of gaseous and particulate pollutants occur close to the occupant and the surrounding air. These results were reported when the pollution source was located either 1 m above the floor (similar to the pollution source in the present study) or it was located near the occupant's feet. In contrast, the present study shows that there was a concentration gradient in the room. The ultrafine and coarse particle concentrations were lower in the ambient air than at the breathing zone of the simulated sitting occupant. The same tendency was observed for the N_2O gas. These results suggest that when the pollution source is at the same height as the occupant's mouth, mixing air distribution at 6 ACH can enhance the transport of coarse and ultrafine particles into the inhalation zone. Thus, it is not reasonable to use the mass balance equation, which assumes perfect mixing, to determine the variation of the pollution concentration level over the whole space.

In the current study, the lowest personal exposure was observed for the fine particles (0.7 μm). It can be observed also that the measured concentration for these particles was slightly higher in the ambient air than at the mouth of the manikin. The reason for the observed differences might be due to the room air distribution and its interaction with the free convection boundary layer formed around the thermal manikin. This interaction may have

impeded the mixing in the room. This confirms well known fact that the boundary layer is important for the personal exposure as well as the extent of mixing in the background (Licina et al., 2015; Melikov, 2015). Depending on the background pollution distribution the free convection boundary layer may enhance the exposure or may reduce it. It may also not affect the exposure (ideal mixing). Since, the room air distribution is difficult to control an advanced air distribution supplying clean air to the breathing zone is recommendable (Melikov, 2016). Localized exhaust methods can be also used to remove particles from active indoor sources such as the human body and exhaled air (Bivolarova et al., 2016; Bolashikov et al., 2015).

Overall, the results in Figure 2 show similar distribution of the tracer gas and the three sizes particles. A recent study by Beato-Arribas et al. (2015) reported that in a hospital isolation room with mixing air distribution (12 ACH), the use of CO_2 tracer gas can represent the airborne behaviour of bioaerosols. Rim and Novoselac (2009) reported that in a stratified flow distribution of 0.03 μm and 0.74 μm particles measured at the occupant's mouth behave similarly to SF_6 tracer gas, this did not hold for the particles of 3.2 μm. In the current study, the lowest difference (5%) was observed at the mouth of the manikin between the normalized concentration values of the tracer gas (N_2O) and particles with size of 3.5 μm. The discrepancy between the results is probably due to differences in the experiments, including different characteristics of the boundary layer and thus its abilities to transport pollution and background room air distribution. Licina et al. (2015) has reported that the free convection boundary layer and personal exposure depends strongly on posture of the manikin and its clothing, chair design and other personal factors. The uncertainty of the measurements and repeatability of the experiments is important as well. More research on this topic needs to be undertaken before the association between gases and aerosols is more clearly understood.

5 CONCLUSIONS

The present study focuses on comparison of dispersion of tracer gas and aerosols with different size in the case of room with mixing air distribution.

The results show relatively small differences in tracer gas and aerosols distribution when the room was ventilated at 6 ACH. The results confirm also that occupant's free convective flow have an important effect on transport of gaseous pollution and airborne particles. Depending on the background air distribution and pollution location the boundary layer around human body may reduce, increase or may not have effect on the exposure to room generated gases and airborne particles. The differences in the measured concentration in the room and at the breathing zone of the simulated occupant indicates that applying well-mixed mass balance models to environments ventilated with mixing air distribution may lead to incorrect estimations of personal exposure.

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